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Application of a Force-Based State Space Approach to Geometrically Nonlinear Planar Curved Beams

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Abstract

In this paper, a force-based curved beam element is presented for geometrically nonlinear quasi-static analysis. The development is based on the Reissner's exact stress resultant theory and its finite strain field for shear deformable curved beams and arches. The presented technique is found by the flexibility based method in which force interpolation functions are used. The state space approach, where a differential-algebraic equation system is solved simultaneously, is utilized as the system solution procedure. In order to improve the element accuracy, a higher order displacement field approximation is utilized based on Lagrange polynomials to evaluate the element flexibility matrix. Finally, the proposed method is validated by nonlinear examples which include some high nonlinear responses as snap backs and steep downward slopes as well as curvilinear beams and shear deformations effects. The comparison of this mixed technique with general displacement-based finite element approach demonstrates some improvement in the accuracy and reliability of the presented formulation with less discritizations. Besides, the shear/membrane locking is alleviated by the element because of using a mixed technique.

Keywords: State space approach, force-based method, planar curved beam

1. INTRODUCTION

Generally, exact and efficient analysis of frame structures, using robust numerical methods should be based on proper nonlinear beam theories such as Reissner's finite strain field [1, 2] which itself is based on Timoshenko's plane cross section assumption. Since the constitutive relations are written for stress and strain resultants instead of stress and strains, the Reissner's beam theory reserves the computational efficiency in comparison with Timoshenko element model.

Many researchers have used this strain field or developed it for nonlinear analyses. Simo [3], Simo and Vu-Quoc [4] formulated and implemented an exact theory for three dimensional shear deformable beam element which reduces to Reissner's in planar case. Saje [5] used the Reissner's kinematic relations to present a finite element formulation for the finite deformation of arbitrary curved extensible shear deformable beam. Pajunen [6] performed large deflection elasto-plastic analyses implementing Reissner's kinematically exact beam theory. Jayachanrdan and White [7] implemented these strain displacement relationships for planar beam using a variable order secant matrix.

As another essential aspect of the modeling, two main points of view through the curved beam simulation have been regarded by researchers. First is using straight beam elements based on straight beam theories which generally require more elements to obtain satisfactory results. (Simo and Vu-Quoc [4], Ibrahimbegovic et al. [8]). Second is the assumption of curvilinear reference line for the curved beam based on slender beam theories to get more accurate results with lower number of elements. (Saje [5], Simo el al. [9] and Ibrahimbegovic [10]). However, the applications of these methods result in some troubles for example in long term dynamic problems including thick or moderately thick beam elements.

For the sake of completeness, it's noted that the early attempts to develop shear deformable curved finite elements were not very successful and the resulted elements might exhibit an excessive bending stiffness under inextensible deformation state and excessive shear stiffness particularly in very thin beam cases. To develop a new shear deformable curved element, it's vital to properly conquer the locking problem for both moderately thick and very thin problems. There are generally four ways to overcome this trouble [11]: (i) The assumed strain technique [12], (ii) The reduced integration scheme [13, 14], (iii) The special hybrid/mixed elements [15], (iv) Appropriate Kirchoff/Mindlin representation with higher order coupled displacement rotation field [16].

Up to now, traditional computer structural analyses have generally implemented stiffness based elements that have some drawbacks associated with displacement field interpolations. This particularly happens in highly nonlinearities and for non-prismatic beams [17]. Due to the time consuming solution processes in